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Multi-layer diffractive Alvarez-Lohmann Lenses for polychromatic applications

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The well-known Alvarez-Lohmann lenses allow a tuning of their focal length by lateral displacement of two phase elements. Diffractive variations provide the advantage of allowing the use of lithographic fabrication methods for replication. We investigate the possibility of enhancing their broadband efficiency by using the multi-layer method, already well known for non-tunable DOEs.

1 Introduction and motivation

Alvarez-Lohmann lenses (ALLs) generate variable wavefronts by lateral displacement of two (or more) optical elements. This allows e.g. creating a lens with tuneable focal length. ALLs theoretically offer large aperture diameters, a compact setup and can be realized as refractive or diffractive optical elements (DOEs). These features make them particularly interesting for imaging applications such as photographic zoom lenses [1]. We will focus on the diffractive variation, since these allow the fabrication via lithographic techniques and offer more degrees of freedom for their design. Especially in the most interesting case of rotationally tuned ALLs the advantages of a diffractive implementation have been shown clearly, e.g. in [2] [3] [4](Fig. 1). Since the strong wavelength dependence of the diffraction efficiency causes stray light and thereby reduces the image quality, we investigate the possibility of improving the lenses' behavior by applying the well-known method of multi-layer DOEs to ALLs.

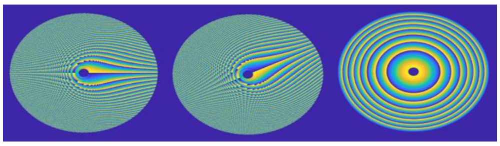

Fig. 1 *Phase-elements (left, centre) and resulting phase function (right) of a diffractive ALL tuned by rotation described e.g. in [3]*

2 Multi-layer DOEs

Diffraction efficiency is defined as the ratio of the intensity within the desired diffraction order to the total incident intensity at the DOE. Phase-DOEs with analogue relief structures theoretically offer diffraction efficiencies of 100%. The phase function of these DOEs is realized by a variation of the thickness d, generating different optical path lengths between parts of the wavefront at different locations of the DOE due to the difference between the refractive indices of the two materials $\mathrm{n}_0, \mathrm{n}_1$. Therefore, the generated phase function $\Phi_{\mathrm{res}}(\lambda)$ strongly depends on the wavelength λ. This can be formulated as a product of a wavelength dependent factor $\Upsilon(\lambda)$ and the phase function Φ for the design wavelength λ_0(1).

$$\begin{aligned}\Phi_{\mathrm{res}}(\lambda) &= -\frac{2\pi}{\lambda}\cdot[\mathrm{n}_0(\lambda)-\mathrm{n}_1(\lambda)]\cdot\mathrm{d}\\ &= \frac{n_0(\lambda)-n_1(\lambda)}{n_0(\lambda_0)-n_1(\lambda_0)}\cdot\frac{\lambda_0}{\lambda}\cdot\Phi\\ &= \Upsilon(\lambda)\cdot\Phi \qquad (1)\end{aligned}$$

The deviation of the resulting phase function for general wavelengths compared with the ideal phase function for the design wavelength causes the diffraction efficiency to decrease dramatically (SiO2-air in Fig. 2).

The aim of the multi-layer method, described e.g. in [5] [6], is to ideally keep $\Upsilon(\lambda)=1$ over the desired wavelength range. This can be achieved by no longer structuring the interface between DOE material and air, but using the interface between two selected materials. Their dispersive behaviour needs to be selected such that the variation of the difference between the refractive indices compensates for the variation of the wavelength itself (1).

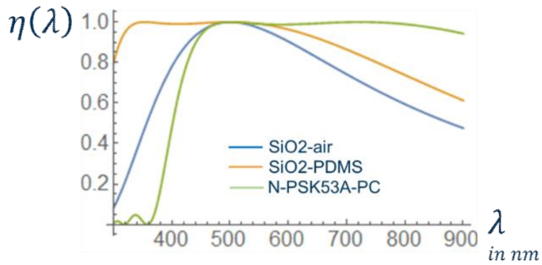

Fig. 2 *Theoretical diffraction efficiencies $\eta(\lambda)$ for a single DOE with analogue relief structures for different combinations of materials, calculated by: $\eta(\lambda)=sinc^2[\pi Y(\lambda)-\pi]$*

3 Structure and possible materials of a multi-layer ALL

To enhance the broadband efficiency of the ALL, each of the phase elements must be realized as a multi-layer DOE on its own. The resulting ALL will

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still show the strong chromatic aberration typical for DOEs, only the intensities within the different foci will ideally be the same(Fig. 3).

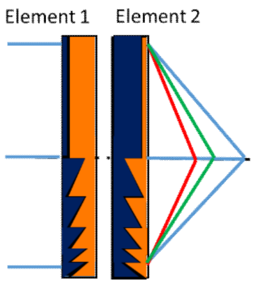

Fig. 3 Basic sketch of a multi-layer ALL

Besides the usual material combination of classical DOEs, fused silica (SiO2) and air, Fig. 2 shows two examples of materials chosen according to the multi-layer method. The advantage can be seen clearly. Since there already is much experience with this combination, the fused silica-PDMS variation will be investigated more closely.

4 Simulations

It can be expected that the resulting diffraction efficiency for the multi-layer ALLs will differ from the theoretical efficiencies shown in Fig. 2. This is due to the quantization of the phase elements and the fact that the ALLs consist of two DOEs positioned one behind the other. To get an idea of the possible results, simulations are performed in Matlab. The first step is to simulate the resulting phase structure at different wavelengths, for different combinations of materials (Fig. 4). The deviation compared to the phase function at the design wavelength can be seen quite clearly. The second step is a FFT-based Fresnel propagation to the respective focal plane for a series of wavelengths. Fig. 5 shows the resulting intensity distributions, the advantage of the multi-layer element is obvious. To quantify the performance, the intensity-sum over the airy-disk of each ALL version was divided by the sum of the intensity within the airy disk for the case of Fraunhofer diffraction at the aperture. This effectively means a comparison with the diffraction limited behavior. Fig. 6 shows the resulting curves which are very close to the theoretical values derived for a single DOE with analogue relief structures. As expected the overall efficiency is lower than the theoretical values, due to the quantization and the propagation through two consecutive DOEs. However, the advantage of the material combination of SiO2 and PDMS is demonstrated clearly.

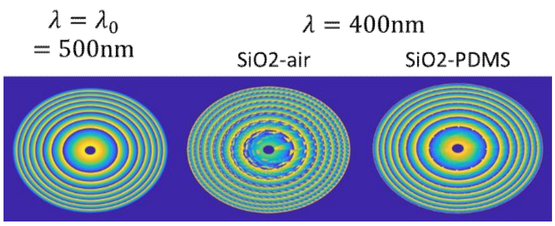

***Fig. 4** The resulting phase functions for different wavelengths and different combinations of materials*

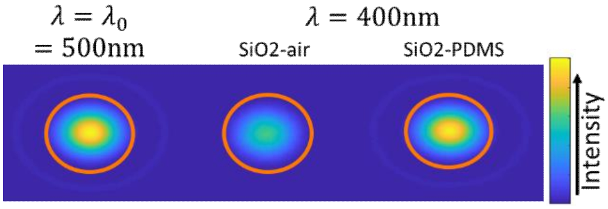

***Fig. 5** The resulting intensity distributions in the respective focal plane, orange circle marks the theoretical airy-disk*

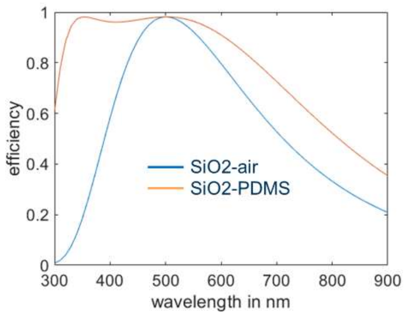

***Fig. 6** Resulting efficiency curves*

5 Conclusion

The results of our investigations show the potential of applying the multi-layer method to ALLs to enhance their performance in broadband applications such as in imaging systems. The next aim is to design and fabricate prototypes for experimental analysis of the simulations' results. The main challenge will be the necessary etch-depth. Caused by the small difference of the refractive indices, for the combination of SiO2-PDMS this depth will be about 18,9 µm for a phase step of 2π. Enhanced techniques for plasma etching enable such etching depths with excellent aspect ratio and surface quality [7].

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